A Flexure Motion Stage System for Light Beam Control

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Abstract: This paper presents the design of an improved tip-tilt-piston compliant/flexure motion stage for steering light beam. The motion stage is actuated by three linear stepper motors in an open-loop control. Using a laser and optical setup, the completed device was tested by making it steer a laser beam, effectively demonstrating its range of movement and level of precision. The testing has proved that the new motion stage system has a maximum bidirectional rotation range of at least 2.89° with a precision and repeatability of 0.0213°, demonstrating a micro-positioning ability.

Keywords: Flexure Design, Open-Loop Control, Light Beam Steering

I. INTRODUCTION

Compliant/flexure mechanisms have advantages including no mechanical backlash, no friction and monolithic fabrication [1], compared to their rigid-body counterparts. For these reasons, flexure mechanisms are often preferred over traditional ones when the required range of motion is small. The unique and innovative features of compliant mechanisms make them well suited for a wide range of applications in robotics, opto-mechatronics, and MEMS devices where range of motion is not as important as positioning precision [1, 2]. This paper aims to investigate a tip-tilt-piston (2R1T) flexure motion stage for steering a light beam [3, 4]. The tip-tilt-piston motions are the three degrees of freedom out-of-plane motions. One direct application for the intended device is high-precision laser beam steering where a mirror is mounted to the motion stage and the laser beam is incident on the mirror surface. When the motion stage rotates, the reflected beam can be redirected to provide precise beam motion. This beam-steering function is widely used in additive manufacturing and optical MEMS (micromirror arrays) [5].

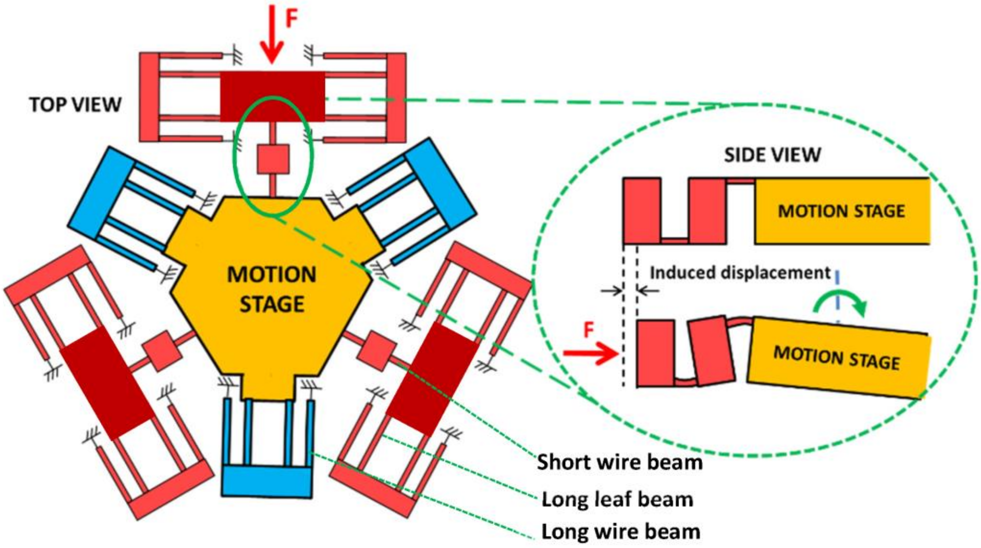
This paper is organized as follows. Section 2 describes the design of the flexure motion stage, clarifying the novelty or improvement of the new design. The control system of the motion stage is presented in Sec. 3, followed by discussing a laser beam steering system and corresponding testing results in Sec. 4. Section 5 finally draws the conclusions. The main contributions of this paper are two folds: a) we present an improved design of the tip-tilt-piston flexure motion stage; b) we present the careful design of a hardware setup to control and experimentally validate the system.

II. DESIGN OF THE FLEXURE MOTION STAGE

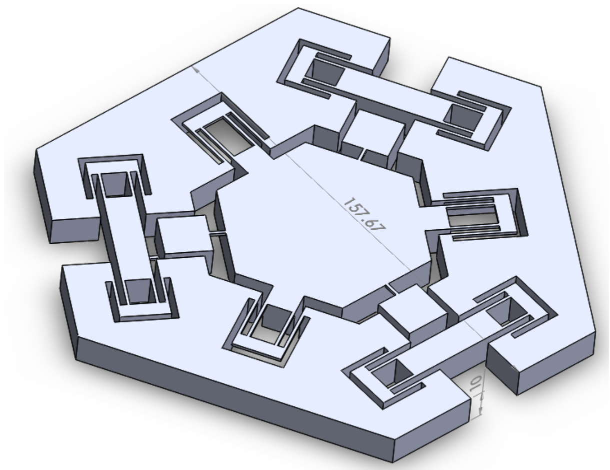
The proposed flexure design is shown in Fig. 1(a), which is compact, monolithic, and tri-symmetrical. It is fabricated using CNC milling machining from a piece of Polycarbonate plate without using any assembly (Fig. 1(b)). The Young's modulus of the material is 2.4 GPa, with yield strength of >60 MPa, and Poisson's ratio of 0.38.

The new design utilizes compliant structures to convert linear actuation (pushing or pulling) on the three outer edges of the model into precise and controllable out-of-plane rotation and translation of a central motion stage. In this way, by varying the input displacement from the three linear actuators, the design is capable of rotating the planar surface of the motion stage in any direction, and making it move up or down like a piston. There are three types of flexure beams being used in the design, including the long (distributed-compliance) leaf beam, the long (distributed-compliance) wire beam, and the short wire beam (as a spherical joint). The kinematic principle of this design was thoroughly explained in [3, 6, 7].

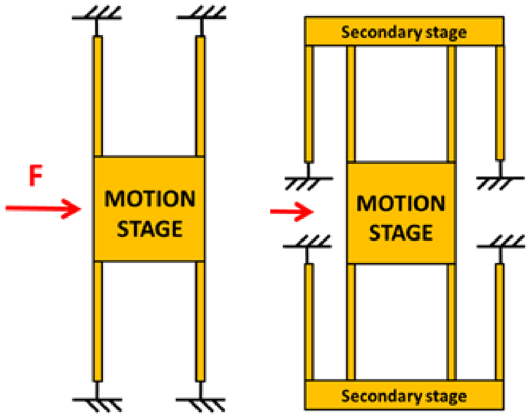
Compared with the multidirectional motion stage designs with active actuations that have been proposed and well discussed in [3, 6, 7], the new design uses double parallelogram modules to replace the corresponding parallelogram modules in this paper. The double parallelogram module is a non-over-constrained design while the parallelogram module is an over-constrained design [8], which are shown in Fig. 1(c). The new design can improve its characteristics mainly in mainly two aspects. Firstly, it allows movement over a larger range of motion while maintaining linear stiffness characteristics, meaning that the relationship between input actuation force and output displacement is linear, due to the non-over-constrained design [8]. Secondly, the actuation force required to produce the same displacement is also less due to the non-over-constrained design, which make the control system less bulky and costly.



(a) The schematic



(b) CAD mode (unit in mm)



(c) Parallelogram module (left) and double parallelogram module (right)

Fig. 1 Integrated design allowing for 2R1T movement and in-plane actuation

III. CONTROL SYSTEM OF THE MOTION STAGE

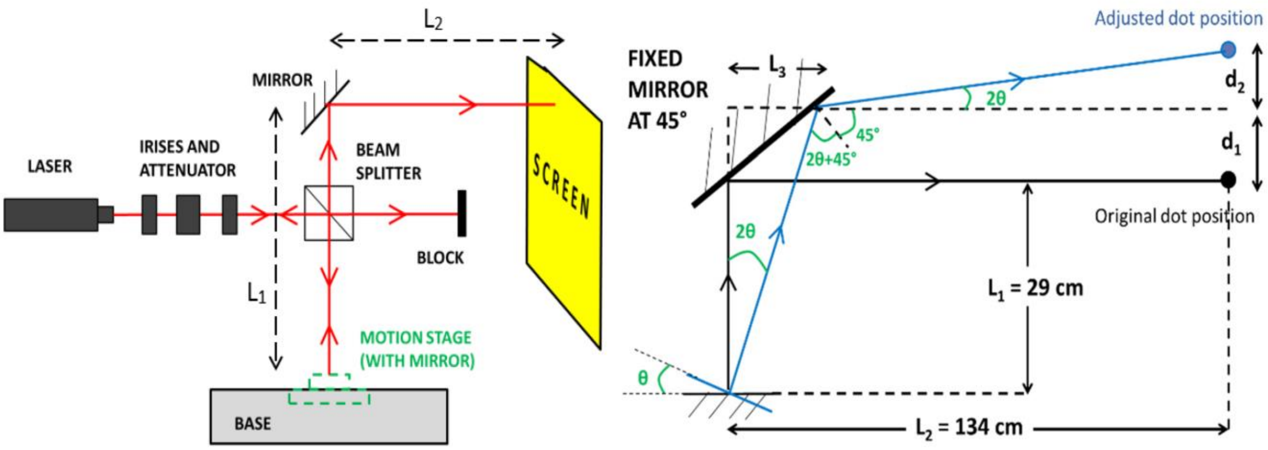
For simplifying the system, open-loop control is preferred over closed-loop control. A solution of actuating the motion stage is to use linear stepper motors, which are well suited for open-loop control, as the step length of a motor is known and the number of steps applied is precisely controlled by the input square wave signal [9]. The stepper actuators allow for a large range of motion and are generally suitable for micro positioning [9]. Other typical actuation methods [5] for flexure motion stages are summarized in Appendix A.

Three small linear motors are therefore selected as the actuators for the device. Their key specifications are the compact size, the maximum load of 58 N, full step of 0.0167 mm, positioning accuracy <10µm, and its bidirectional movement capabilities.

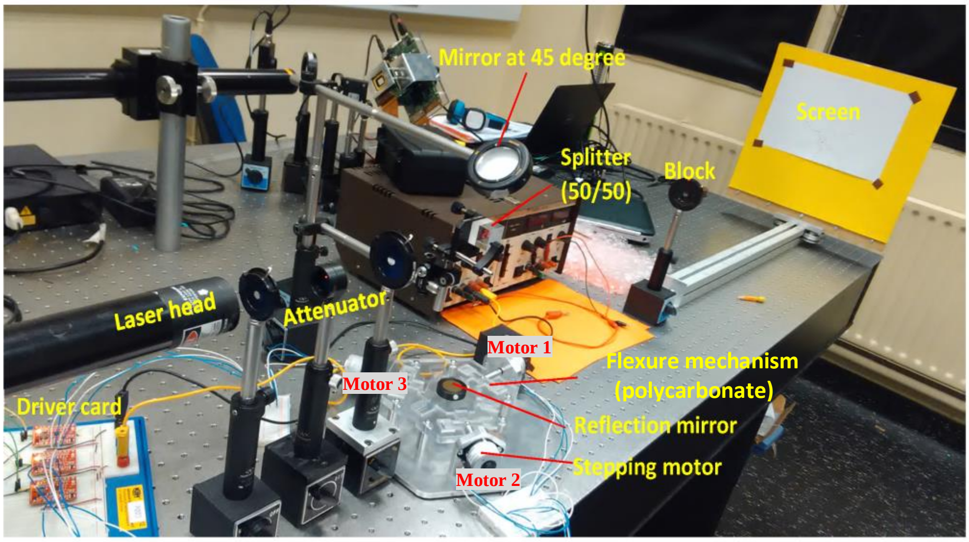
The drive circuit for the motors enables current switching in the coils in a multi-phase sequence, i.e., the number of phases depends on microstep setting. This is what causes the motor shaft to move. Each motor needs two inputs from the Arduino: one is a digital high/low that controls direction, the other is a square wave signal that activates the stepping of the motor (1 step per rising edge of the input). The frequency of the step signal dictates the speed: it is set arbitrarily to 1 kHz using the Arduino code (this speed was fast enough for experimental purposes). By default, the drivers are set to allow the stepper motors to move by microstepping, i.e., the motor moves by 1/16th of a full step, equal to 1.04 µm. Since the positioning accuracy is ~10 µm, the motor can move in multiples of 10 steps to ensure precision.

IV. LASER BEAM STEERING SYSTEM AND TESTING RESULTS

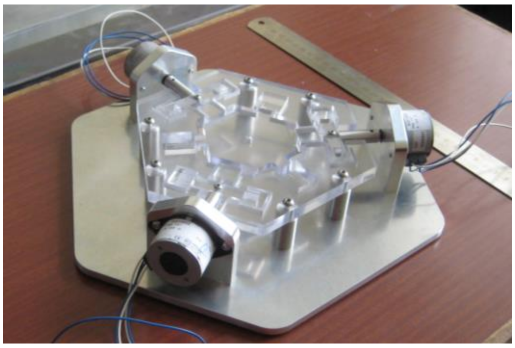
A high reflectivity mirror is attached to the center of the motion stage for this experiment, which will determine the precision and usability of this device for one of the key applications – beam steering. The optical setup in Fig. 2 shows the path of the laser beam and how its ultimate destination point is controlled by the motion stage rotation. The laser used is a 13 mW, 633 nm (red) HeNe device, and it is attenuated to be 0.13 mW for eye safety.



(a) Schematic of beam steering using the motion stage



(b) Hardware setup of testing system



(c) Close-up of the fabricated monolithic flexure prototype

Fig. 2 Optical setup for beam-steering experiment

By typing a command to the Arduino serial, the actuators can move a discreet number of steps from the neutral position, rotating the mirror by a particular angle relative to the x-y coordinate system (on motion stage plane). This causes the laser dot to move on the screen by a distance that is related to the rotating angle by trigonometry, and in a direction that is defined by the motor(s) that are activated and by how much they displace the mechanism. The relationship, between rotation angle (θ) of the motion stage and displacement of the dot from the center point d, is derived mathematically based on Fig. 2(a). L_1 and L_2 are lengths measured from the optical setup (see Figure 2). The angle that the beam reflects off the mirror motion stage is twice the angle θ, and when this reflected ray reflects off the second mirror the new reflection angle is double the previous one. With these relations, it can be written that:

$$\theta = \arctan(\frac{d_2}{L_2 - L_3})/2 \tag{1}$$

With Equation (1) it will be possible to calibrate the prototype device by finding its rotating angle response for the given input displacement.

To find the precision of the mechanism, the simplest method is to do a repeatability test. Move the dot to a position, take note of the position in space and the input displacement settings, and after moving the dot around, re-enter the same actuation settings and see if the dot has moved to the exact same position as before. Another test for the precision/resolution is to enter a very small input to check if the mechanism responds by rotating the motion stage. This will be very difficult to see by eye, as the rotation in this case should be only a tiny amount, which will barely move the dot (at this short distance). Interferometry might be the best way to check this as the closed-loop feedback.

The prototype's beam steering capabilities were tested using the setup described above. The motion is now proven to be highly repeatable: many dot positions were tried and the device was able to replicate them with great precision – no position difference between points with the same actuation settings could be observed by eye. Calibration of the response to motor input displacement was also done by marking the screen and measuring the dot displacement. The calibration results are shown in Figure 3 for each individual motor activated to produce displacement in steps of 100; the shaded zones are areas where the dot position output is the result of two separate motor inputs. These form an approximately linear pattern.

The maximum rotation of the mirror stage can be found in Fig. 3 using the earlier formula:

$$\theta \approx \arctan(\frac{6.76}{134})/2 = 1.44^{\circ} \tag{2}$$

This is the case when motor 1 inputs 700 steps (=0.7 mm). This value is very close to the theoretical value of 1.65° that can be calculated using the mode developed in [3] for an input displacement of 700 µm.

The next test is to find out the minimum input that it takes for the mechanism to respond. Since the minimum input is on the order of 1 – 10 µm, it will be impossible to see the resulting beam movement with the naked eye. To see the result, a Michelson 2-beam interferometer is set up as in Fig. 4.

Only a rudimentary understanding of interferometry is needed for this simple test. The optical setup is changed slightly as shown by the right side of Figure 4. The block is replaced by a mirror, and the screen is replaced by a CMOS detector. This new setup causes two beams to converge on the same point and interfere. One of the beams is the same as before, the other one does not reflect off the mirror stage so it acts as a reference. The CMOS camera is used to detect the interference, which can be seen by the pattern of light and dark fringes that results when two out-of-phase beams meet. As the tilt angle increases, the spatial frequency increases, which correlates to the number of fringes per mm. This pattern can be observed in Figure 4, confirming that the mechanism is sensitive enough to respond to an actuator displacement of approximately 5 µm (see the change from Figure 4(a) to 4(b)). Since the positioning accuracy of the motors is ~10 µm, this means that the mechanism's response has a higher resolution than the motor input. To truly test the precision of the mechanism, higher resolution actuators (or closed-loop position tracking) will be needed.

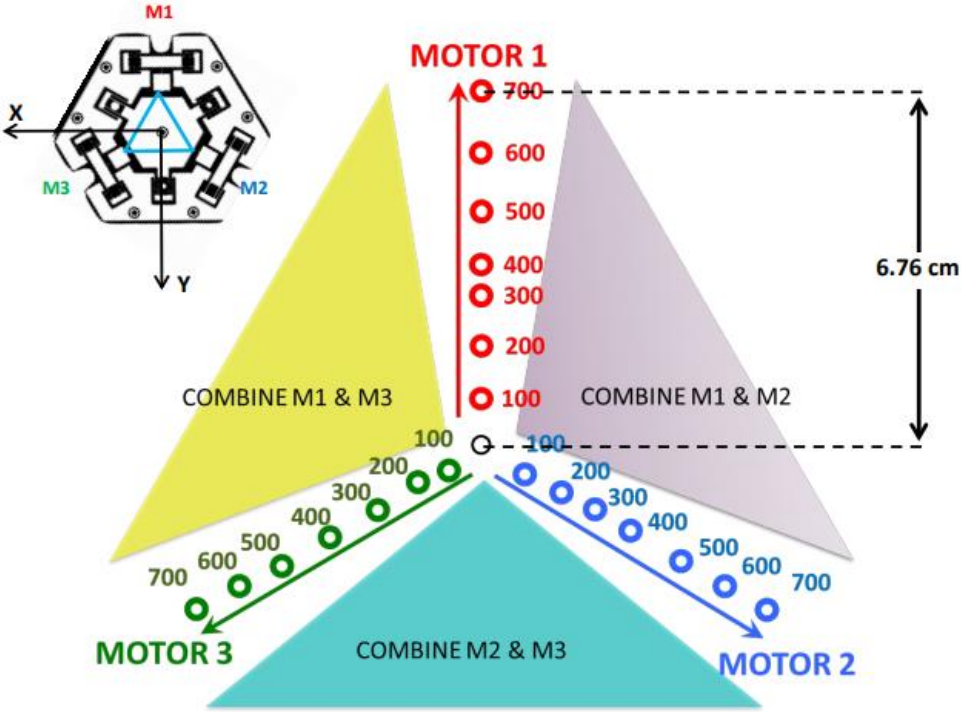


Fig. 3 Testing data illustration on the screen

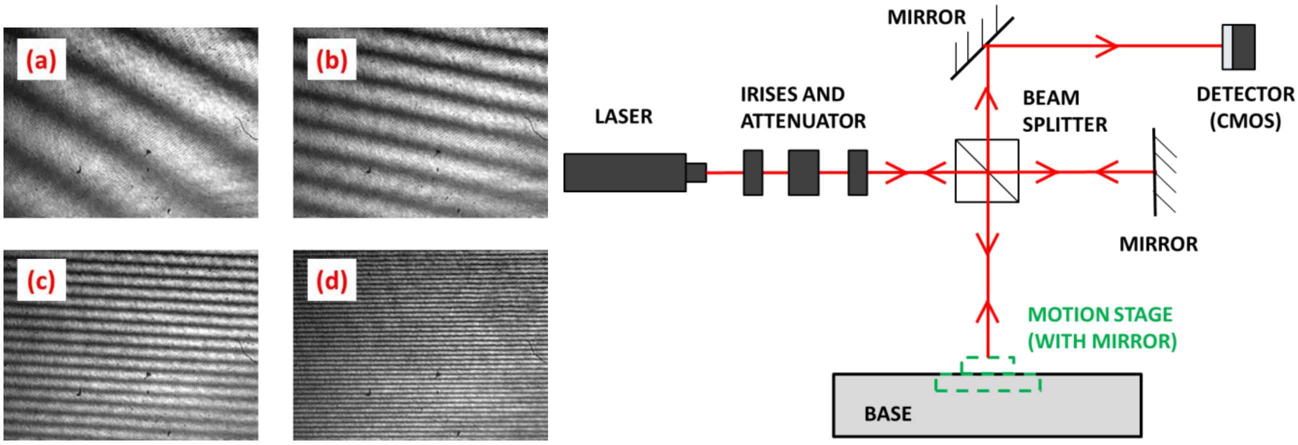


Fig. 4 Gauging the device precision using the interference pattern. CMOS images for: (a) Motor 1 input = 20 ± 10 µm; (b) Motor 1 input = 25 ± 10 µm; (c) Motor 1 input = 50 ± 10 µm; (d) Motor 1 input = 100 ± 10 µm

V. CONCLUSIONS

A new compliant motion stage was designed and tested. Appropriately sized actuators to supply force to the mechanism were identified and sourced; a driver circuit was built for these actuators and open-loop control implemented using an Arduino microcontroller. A simplistic yet functional user interface was created so that the user can enter commands on the keyboard indicating which motor to activate and how much displacement is necessary, and have these commands immediately carried out.

The physical components including the compliant mechanism, the motors, and the drive circuit were all integrated into one design, linked by a steel base fixture. This design was light, compact, tri-symmetrical, and elegant. The device was tested by using it for steering a laser beam – one of the most important applications for a multi-axis compliant motion stage – and it demonstrated excellent precision and repeatability.

Future work focuses on the fast light beam steering and design of a closed-loop control system for the current flexure design. In addition, the flexure design should be further optimized for large range of motion and compact footprint.

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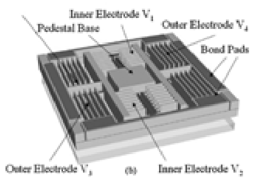
APPENDIX A: OTHER ACTUATION METHODS FOR FLEXURE MOTION STAGES

Electrostatic Plate Actuators		*Electrostatic Comb Actuators*		*Thermal Actuators*	
Use attractive electrostatic force between oppositely charged plates to create linear motion. Force generated by actuator is $F_e = \frac{V_s^2 \varepsilon_0 \varepsilon_r A}{2(x_0+x)^2}$		*Same principle as the plates, but this time using comb-like structures which amplify the electrostatic force*		*Use layers of materials in a thermal strip, where each material has a different thermal expansion coefficient. When heat is applied to the strip, it bends towards the side that expands less*	
ADVANTAGES:	**DISADVANTAGES:**	**ADVANTAGES:**	**DISADVANTAGES:**	**ADVANTAGES:**	**DISADVANTAGES:**
• Simple and straightforward design • Easy to control force by adjusting voltage • Very simple compliant structure is needed • Works excellently for small-scale • The standard choice of actuator for DMDs and other micro-devices	• Distance between plates must be very small, greatly limiting ROM • Force generated by actuators decreases massively as airgap increases • Can only pull plates together, can't push them apart • ε_0 is 8.9 x 10^{-12}, which means a huge voltage would be needed to create any meaningful amount of force relative to a large model	• Easier to control than the plates • Allows for much greater separation distance, therefore greater ROM • Much greater force output than plates, this form of actuation has been proven to work on larger structures 	• More complex structures are needed for the CM • Teeth of comb can get in the way of motion, limiting ROM • Decoupling is needed to ensure teeth do not get in the way	• High force output is possible • Easy to fabricate on both large and small scale • Robust design	• Slow speed, less than 1 kHz maximum, which is much less responsive than the other methods • Ambient temperature could interfere • Low accuracy and precision • Complex thermal decoupling needed to prevent heat from one section spreading to others
VERDICT: While the plates are good for very small devices, they simply won't be able to generate enough force and the ROM would be too limited for a larger scale (about fist sized) model. Not feasible.		**VERDICT:** More viable than electrostatic plates because the force generation potential is much greater, however the fabrication of such a comb-like device could be beyond the limits of the workshop available. Unlikely to be used for the final design.		**VERDICT:** There are too many variables to control for, this makes it an imprecise design. Also would need to allow for cooling time between movements. Possible as a backup option, not preferred.	

Lorentz Actuators (Electromagnetic)		*Piezoelectric Actuators*		*Shape-memory alloys*	
Trace coils attached to the motion stage in conjunction with small magnets: current in the coil in presence of magnetic field induces movement $F = q\vec{E} + q\vec{v} \times \vec{B}$ *(Right-hand rule)*		*Uses materials that expand or contract when a voltage is applied across them*		*Based on a special alloy of Nickel, tin, and titanium called Nitinol which has the ability to be deformed and then return to its original shape when heated*	
ADVANTAGES:	**DISADVANTAGES:**	**ADVANTAGES:**	**DISADVANTAGES:**	**ADVANTAGES:**	**DISADVANTAGES:**
• Higher force output than electrostatic methods • Bipolar actuation: can push and pull • Driving current is proportional to force • High speed, even for multi-DOF systems • Excellent accuracy and precision • Non-contact actuation means no decoupling is necessary	• Length of coils is limited for small devices, decreasing the force output • Magnetic fields can induce crosstalk and other unwanted effects • Power/heat dissipation in coil is significant • Fabrication can be difficult	• High output force potential for a low input current • Less power needed than thermal or Lorentz • Less heat generated • Commercially available in small sizes – easy to order online	• Cannot produce much displacement, requires mechanical amplifier • Contact-based actuation means decoupling mechanisms are needed	• Lightweight, not much material needed • Can produce a significant amount of force & generate large displacement when heated	• Seems to require a lot of current before it is heated enough to begin restoring force • As slow as thermal if not slower • Decoupling needed • Produces a lot of heat • Nitinol is very expensive, even in small amounts
VERDICT: While acquiring the right size coils and cores for the magnets might prove difficult, this method seems to be the most viable so far, with the pros outweighing the cons. Feasible.		**VERDICT:** Non-contact actuators would be preferred as that would simplify the design, but this method is still doable assuming the appropriate parts and amplifiers can be purchased. Viable for use.		**VERDICT:** Far too many downsides, would be very difficult to implement properly. Requires initial deformation before force can be produced. Far too slow. Unfeasible.	